



Design and performance analysis of a hybrid solar tricycle for a sustainable local commute



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ABSTRACT

Fossil-fueled transportation is the main type of transportation used all over the world. Transportation in the United States consumes almost one third of global transportation energy and is one of the major contributors to CO₂ emissions. To deal with ever increasing environmental pollution and reduce energy consumption, a solar Trike design is presented in this paper to offer an alternative means of transportation. The solar Trike offers a higher occupancy rate, speed and travel range that can satisfy the needs of the local commute. The design, economics, sustainability and performance analysis of the solar Trike is presented in this paper.

The dimension and power requirement of the solar-powered tricycle was determined based on aerodynamic force, rolling resistance, expected payload, travel velocity and distance and solar irradiance. A CAD model was built and analyzed for sustainability before building the prototype. Test run results of the prototype suggested the technical feasibility and practical applicability of the design. An LCA was performed to evaluate environmental impacts during various stages of the product life: manufacturing to disposal using SolidWorks Sustainability software. Manufacturing, operating and environmental costs are analyzed for economic viability of the design. The annual costs of CO₂ emissions, design and installation, annual maintenance, and costs to store the power for one full charge amount to \$417. With a travel range of 37.1 km on a full charge, the proposed solar-powered tricycle is able to meet more than 90% of all trip distances in the USA. The proposed solar powered tricycle reduces energy consumption by more than 41%, as well as decreases CO₂ emissions by more than 75%, in comparison with the railroad, the best mode of existing transportation.

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1. Impacts of transportation on the environments

Noise, air pollution, climate change, disturbance to the natural landscape through separation and isolation of urban areas, water and ground sealing, reduction in natural visibility and accidents are some of the undesirable outcomes of transportation [1]. These factors are generally grouped under energy consumption and the resulting pollution for economic and environmental sustainability.

Fuel or energy consumption, CO₂ emissions and carbon footprints are usually referred in transportation sustainability. As per the World Energy Council more than 60% of 2200 Mtoe (million tons of oil equivalent) oil consumed globally goes to the transportation sector, and road vehicles consume the majority (76%) of it [2]. Davis et al. state that the total energy consumption of the U.S. transportation sector for 2010 is 696.491 Mtoe, which is almost one-third of the world's used transport energy per year [3]. Emissions from transport – above all road and air traffic – embody a significant share of the overall emissions. The transport sector alone creates 22% of the total CO₂ emissions – 80% from road transport, with more than 55% from private cars [5]. In general, the energy consumption and emission values are dependent on the occupancy rates of the used vehicle. CO₂ is measured in gram per passenger (g/passenger) for an effective comparison of the different modes of transportation. A summary of the energy used and CO₂-emissions for different modes of transportation is given in Table 1 for a comparative understanding.

As shown in Table 1, a single occupancy car consumes 5080 btu (British Thermal Unit) (8.58 MJ), whereas the most efficient heavy rail consumes only 858 btu (1.45 MJ) per passenger mile. CO₂ emissions from the cars and van pool are 608.2 and 156.1 g/passenger-km, respectively [4].

Carbon foot print is also used for environmental analysis, which is an equivalent emission in gram of CO₂. The higher carbon foot print per capita of developed countries (United States 17.6, France 5.6, Germany 9.1, Japan 9.2 and the Netherlands 11.0 metric tons) suggests an immediate need for reducing waste and energy consumption [6]. The exponentially growing trend of energy demand to support economic growth and development is depleting the fossil fuel reserve and generating a tremendous amount of pollution. Various methodologies have been developed to minimize these undesirable impacts, and it is commonly agreed that environmental factors need to be considered as an important long-term issue in the transport policy, planning, and decision-making process [5]. Improving efficiency, reducing consumption, and changing wasteful habits are the keys to sustaining the energy

supply. Higher occupancy vehicles result automatically in higher energy efficiencies and less CO₂ emission per passenger mile. Although car pooling and public mass transportation have better environmental prospects, they are the least favorable modes of transportation among commuters citing more travel time, loss of privacy and limited travel flexibility. The motivation of the researchers is to come up with a design that allows personal freedom in travel, minimizes the waste of resources and serves the majority of drivers by meeting their main transportation need.

Fuel efficiency of vehicles has improved significantly in recent years. However, a shift to bigger and more powerful engines and travel at lower occupancies partly ruin the benefits of the realization of fuel efficiency advancements [7]. Increasing passenger transport in most countries at the rates equal to GDP has pushed the environmental impacts to the limits [5]. In the United States, a weighted average trip distance is 9.4 miles (15 km) [8]. The most used means of transportation are either a car, truck, or van with more than three quarters of the commuters driving on their own [9], suggesting a significant waste of transportation space. Aside from the most pronounced use and reduction of non-renewable resources and general emission problems, other environmental issues such as operational pollution (taking away bikes and walking spaces) and land intrusion (road congestion) also need to be considered.

1.1. Sustainability in transportation

The importance of sustainability is recognized by various governments, and they are introducing different measures to lower emissions and energy consumption. Encouraging the use of electric vehicles, mandating the emission level in fossil fueled vehicles and promoting use of alternative renewable energy sources through financial incentives are some of the approaches used to reduce the emission impacts. Mostly, electric vehicles are largely considered (or misunderstood as the only) as a means for sustainable or environmental friendly mode of transportation.

In the beginning of the 19th century when the first electric-powered vehicles were built, they outnumbered fossil fueled vehicles. However, due to their poor range and unfavorably low speed, electric vehicles soon disappeared. With growing concerns about climate change and environmental pollution by conventional-powered vehicles during recent years, research on electric vehicles is undergoing. Lately, the development of electric-drive-vehicles is enjoying significant growth in the United States [10] and Europe [11]. Hybrid electric, electric using fuel cells or permanent power-supplied vehicles like trolley busses or trams using overhead wires are some examples of electric vehicle developments [12]. In the last couple of years, many car manufacturers have added electric vehicles to their production lines. A list of electric vehicles available on the Unites States market is shown in Table 2.

As shown in Table 2, various models of electric cars are available with different price ranges and seating capacities. The minimum power rating is 60 kW and the lowest seating is four. Benefits of electric-powered vehicles are lower GHG emissions and less noise pollution. In these electric cars, internal combustion engine of a fossil fueled car is replaced by a smaller electric motor and battery, facilitating a compact design, which is beneficial in driving and parking in narrower spaces mainly in urban areas. Cost is a crucial factor in sustainability; in general, the higher cost of a

Table 1
Energy use and CO₂ emissions for different modes of transportation [4].

Mode of Transportation	Btu/pass-mi	MJ/km	CO ₂ g/pass-mi	CO ₂ g/pass-km
Van Pool	1,300	2.2	97	156.1
Heavy Rail	858	1.45	151	243
Commuter Rail	1,493	2.52	164	263.9
Car Pool – 2 Persons	2,540	4.29	189	304.1
Trolley Bus	1,294	2.19	228	366.9
Domestic Air Travel	3,138	5.3	234	376.5
Car – Average Trip	3,215	5.43	239	384.6
Transit Bus	4,391	7.42	308	495.6
Car – 1 Person	5,080	8.58	378	608.2

Table 2
Summary of electric cars.

	2015 Tesla Model X [13]	Nissan[14] LEAFS	Chevy[15] Volt	Mitsubishi i-MiEV[16]	Toyota RAV4 EV[17]
Power(kW)	60–85	80	63	47	115
Body type	SUV	SUV	Coupe	Hatchback	SUV
No. of seats	7	5	4	4	5
Range (km)	338–434	121	56	100	167
Battery (kWh)	60–85	24	10.3–16	16	41.8
Base Price ^a	TBA	\$21,300	\$40,280	\$22,995	\$49,800
km/kWh	6.4	4.4	5.4	6.2	3.99

^a After \$7,500 federal tax credit.

product is associated with the higher energy consumption directly or indirectly during one or more stages in the product life. Initial costs of most electric vehicles are still high, limiting access to the common public. Electric vehicles are relatively compact but the occupancy rate is still lower; they are almost the same compared to the fossil fueled cars in wasting rider space because of the single person driving a car with the seating capacity of four.

Use of renewable energy sources is one facet of sustainable transportation [18]. Energy efficiency and the use of renewable energy are some of the measures implemented by various local governments around the country to reduce travel delay, congestion, and pollution [19]. Limiting new vehicle licenses (in China) and linking transport land use planning for sustainability (Curitiba, Brazil; Portland, Oregon; and Vancouver, Canada) are some of the other approaches taken to combat the pollution problem around the world. The use of mass transit in urban areas reduces energy consumption and increases the occupancy rate. Companies are also producing solar powered mass transit. For example, Sunpods Inc. produced the first solar power-assisted system for buses [20]. Sustainable measures have also been taken in water transportation, for example, solar boat [21].

Locally, Pueblo County in Colorado is looking for alternative transportation choices; a more sustainable vehicle could satisfy the transport needs of most workers. Lane sharing on roads with designated walking–bicycle lanes has encouraged people to walk or ride bicycles on the road avoiding the need of cars to travel around the neighborhood. Bi- or tricycle lanes to support a zero emissions program are to be integrated into a new development and transportation infrastructure improvements plan. This and similar kinds of initiatives in various locations around the country can foster the use of the solar Trike and provide an opportunity for solar tricycle development.

1.2. Pollution costs measurement

To mitigate the pollution problems, cost of pollution also needs to be incorporated into the product cost. To quantify air pollution effects and incorporate the environmental costs into a traditional business model, Emission Trading System (ETS) is developed. ETS is used in EU countries as a way of assessing CO₂ emissions in monetary units and is based on “cap and trade”. This provision is intended to allow companies and institutions to trade greenhouse gases [22]; companies can sell and buy emission rights in the market place. Limits are set as per the inspiration of Kyoto Protocol as binding obligations on industrialized countries to decrease emissions of greenhouse gases [23]. The emission certificates are traded at the European Energy Stock Exchange (EEX). A price for emission certificates, usually Euro per ton (€/t) of CO₂ emission, is settled by the market. The United States did not join the Kyoto Protocol, and is not required to abide by any of these regulations. However, various emission control regulations are in place to save

the environment. Preventing pollution might be the best strategy, and needs to be considered from the very beginning of the design process – product conceptualization.

1.3. Sustainable design

Sustainable design is an approach to realize the essential balances between environments, society, and economy through engineering design practices. Life Cycle Analysis (LCA) is used as a design tool for incorporating environmental impacts considering every stage of the product life: manufacturing, transportation, use, and disposal. If environmental and waste issues are not well planned right from the beginning in the design process, production as well as waste management and recycling may become complicated [24]. Selecting materials owing to economic pressure can lower the price but it might generate more pollutants, requiring high waste disposal costs to avoid a compromise to human health and the environment. It is the designer's responsibility to lay out the foundation for sustainability of a product.

In this research, a prototype was built and tested in a project laboratory at Colorado State University, Pueblo. SolidWorks software is used for designing and performing a sustainability analysis by incorporating environmental factors in various stages of the Trike life cycle: manufacturing, transportation, use and disposal. Comparison of the solar-powered tricycle with other modes of transportation is performed using carbon dioxide (CO₂) emissions and energy consumption per passenger mile as a part of the sustainable design. Travel range and occupational rates are also investigated. Trike is expected to have an enough travel range to cover most of the daily travel needs of the local commuters, decrease reliance on fossil fuel, help to reduce pollution and foster healthy life style. An economic model is presented for cost analysis, which is used to evaluate the affordability of the tricycle for the general public, either as a sole means of transportation or as a substitute of a second car for local drive.

The rest of the paper is divided into two sections. The design section includes the load and power requirement calculations and sizing of the Trike. LCA is used for the environmental impacts assessment using carbon footprint and energy consumption, etc. The test run results summarize the travel range and run time of the Trike and present a comparative study of the Trike to other modes of transportation.

2. Tricycle design and analysis

Recumbent [25], upright [26] and multi-person tricycles [27] are commonly available in tricycle designs. Cabin comprising solar powered tricycles provide shade to the driver in addition to propelling the vehicle [28]. A Pedal/Motor Powered Tricycle design comprises a three-wheeled vehicle combined with a rack for holding a solar panel and has both manual and power mode [29]. A solar panel mounted to a luggage [30] and a motor on the wheel [31] are some of the other configurations of existing designs. A tricycle with a PV panel mounted on the canopy offers shade to the driver providing some protection from sunlight or rain, storage room for bags or other objects and better safety in case of accidents. The canopy design with concave seat increases the comfort to the driver [32]. Design information and performance of these vehicles are not available and it is not clear whether they are intended for the regular commute or not.

Based on the literature study, geographical location, cost and simplicity, an upright commercially available tricycle frame with hub motor and regenerative braking are selected as basic platforms for the design.

2.1. Design parameters

Traditionally, torque, speed and power needed to meet the travel range are the basics in vehicle design. Cost of ownership and maintainability are some of the factors. Lately, environmental impacts have also been considered in a sustainable design approach. A solar powered tricycle (Trike) is proposed in this paper, which uses solar energy to power it on its own.

Torque that is required to drive the Trike is based on wind drag, gravitational force and rolling resistance. Aerodynamic drag is proportional to the product of the frontal area (A) and drag coefficient (C_d) [33]. Rolling resistance occurs due to continuing deformation of tires, which is proportional to tire flexibility and surfaces in contact. A less elastic and more flexible tire creates higher rolling friction [34]. Normal components of the weight (vehicle, rider and luggage) contribute to rolling resistance. The power requirement to propel the Trike is given as:

$$P = 0.5\rho C_d A v^3 + mg(c_{rr} \cos \theta + \sin \theta)v \quad (1)$$

where, P is power (Watt), ρ is air density (1.29 kg/m^3), C_d is drag coefficient, A is effective frontal area in m^2 , θ is slope of the road, mg is weight, v is velocity of the Trike and c_{rr} is coefficient of rolling resistance

As shown in Eq. (1), power depends upon area, velocity, weight and slope of the road.

2.1.1. Torque and power

Torque is dependent on the length of the radial arm and a tangential force (F_t) [34]. During pedaling, the angle between the tangential force and the radial arm varies: force application is constant and vertical in the upright seating position but the direction of the arm is changing in a circle as shown in Fig. 1.

The average torque ($\bar{\tau}$) is determined as:

$$\bar{\tau} = \frac{1}{\pi} \int_0^\pi rF \sin(\theta) d\theta = \frac{2}{\pi} rF = 0.64rF \quad (2)$$

The crank-arm length is constant but the application of force on the paddle depends upon the types of seating positions [35]. Upright seating with a 180 mm crank length with a 9.43 rad/s as a non-professional cyclist speed is used for best performance [36]. Transmission ratio between the peddling (cog wheel) and rear-wheel decides the power of pedaling and the speed of the Trike.

With a pedaling cadence of 9.43 rad/s [36], lever arm of 0.178 m, cogwheel radius (r_{cp}) of 75 mm, rear sprocket radius (r_{cw}) of 40 mm and wheel radius of 305 mm as shown in Fig. 2, the transmission ratio will be 0.533.

The transmission ratio of almost half suggests that the angular velocity of the wheel is half the angular velocity of the paddle.

In electric motors, the angle between force and the lever arm vector stays constant. The Trike is designed for a maximum velocity of 13.4 m/s. Power on the wheel is based on the amount of the torque required to maintain the ride and the angular speed as shown in Eq. (3).

$$P = \tau\omega \quad (3)$$

A drag coefficient of 1.2 is used considering the larger width and lower seating position on the Trike in comparison to a common bicycle. The effective cross-sectional area of the tricycle is computed to be 0.564 m^2 using a method used by Gross et al. [33]. A Trike speed of 13.4 m/s is used as a reference believing such speed is needed in order to make a notable difference in comparison to other modes of transportation. The relationship between speed and drag force is shown in Fig. 3.

As shown in Fig. 3, the drag force (F_d) is increasing with the speed of the Trike. The drag force of 78.6 N computed at a speed of 13.4 m/s. Normal force is determined by the weight of the Trike

Torque Production Through Pedaling

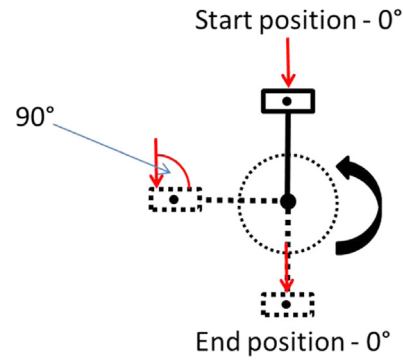


Fig. 1. Relationship between torque, pedaling force and lever arm.

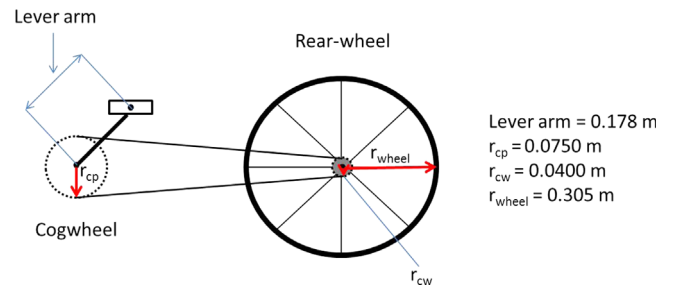


Fig. 2. Connection between pedal cogwheel and rear-wheel cogwheel.

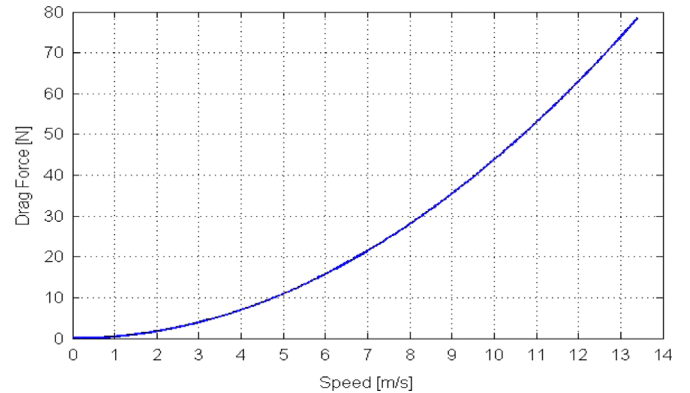


Fig. 3. Relationship between speed and drag force.

(84.3 kg) and rider (137 kg). For a recommended tire pressure of 2.76 bar and velocity of 13.4 m/s, the rolling resistance coefficient (C_{rr}) is 0.00962, and the resulting rolling resistance force is 20.9 N. Drag and the rolling resistance force sums to a total resistance force (F_{total}) of 99.5 N, which is the driving force needed to ride the Trike at a speed of 13.4 m/s on a flat plane.

For pedaling at the speed of 5.39 m/s, drag and rolling resistance forces are computed to be 12.7 N and 18 N, respectively. For a pedal lever arm of 0.178 m, torque at the pedal τ_{pedal} is 3.7 Nm, and with the wheel lever arm of 0.305 m, torque at the wheel τ_{wheel} is 30.3 Nm. Powers for paddle and motor driven are shown in Fig. 4.

As shown in Fig. 4, the power requirements increase with the velocity of the Trike. The power to reach a speed of 13.4 m/s is 1,330 W (1.78 hp) and the power needed for manual peddling at a speed of 5.39 m/s is 65.8 W.

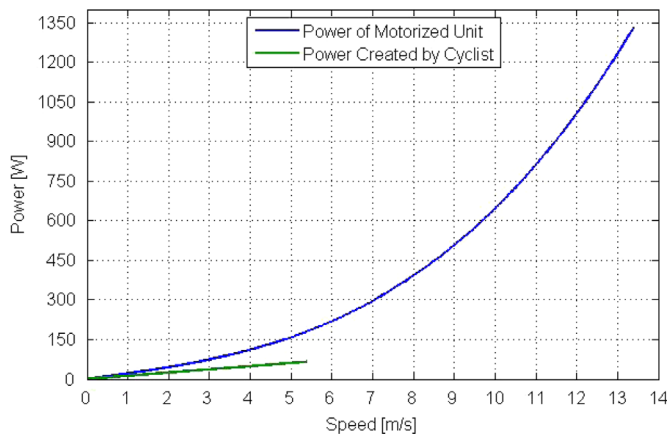


Fig. 4. Power speed relationship for speeds up to 13.4 m/s.

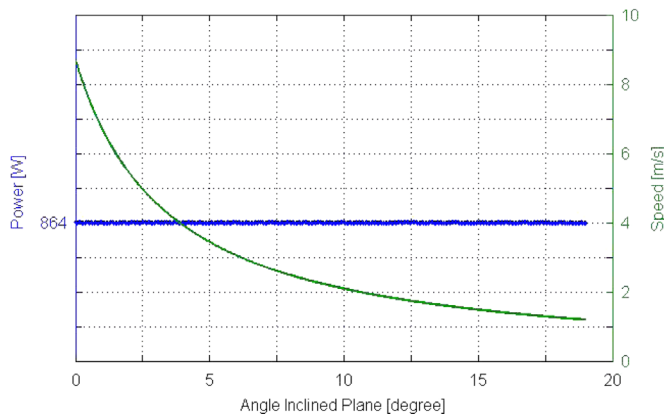


Fig. 5. Speed vs. slope.

So far power requirements were calculated to ride the Trike on a flat smooth surface. However, uneven pavements, bends, up and down slopes are common features of roadways. Specifically, riding uphill requires higher torque and power. This design does not include any gearbox and the speed of the tricycle will decrease in uphill rides to supplement the higher torque requirement. Analysis for an uphill ride is performed next.

The drag force is dependent on the speed and does not vary with the slope of the road. The normal (sine) component of the weight opposes the uphill motion, and the tangential (cosine) component of the gravitational force appears normal to the surface contributing to the rolling resistance [34]. The force affecting the tricycle when going uphill can be summarized as a rolling resistance force, gravitational force and drag force.

Under the assumption that the batteries are able to deliver a capacity of 864 W in combination with the calculated torque at the wheel τ_{wheel} , a theoretical maximum angular velocity of 30.2 rad/s equaling a speed (v) of 8.70 m/s can be calculated. This is the theoretical value for maximum speed on a flat plane with no slope. The effect of slope to the Trike's velocity is shown in Fig. 5. As shown in Fig. 5, speed decreases rapidly as the road slope increases. The maximum speed the tricycle could reach was 8.90 m/s by motor-propulsion. A relationship between velocity, slope and power is shown in Fig. 6.

As shown in Fig. 6, for a given velocity, higher power is needed if the road slope increases. For a constant slope road, one needs to increase the power to speed up the Trike. For either an increase in slope or velocity, additional power is needed. The power needed will be much higher if both slope and velocity increases, simultaneously.

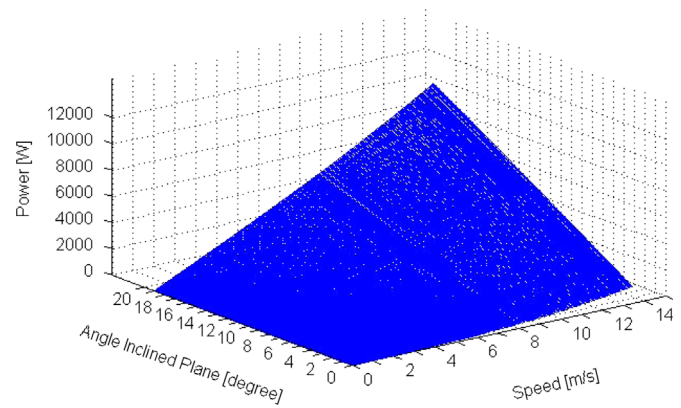


Fig. 6. Power-speed-angle relationship.

Table 3

Summary of the forces at speed of 8.90 m/s in a flat plane.

Important values based on a speed of 8.90 m/s	
Drag force [N]	35
Normal force [N]	2,170
Rolling resistance coefficient [Crr]	0.0092
Rolling resistance [N]	19.9
Total force [N]	54.9
Torque at the wheel [Nm]	16.7
Power at the wheel [W]	490

Table 3 shows the force, torque and power calculated for the experimentally determined maximum speed of the tricycle at 8.90 m/s on a flat plane. The torque and the power the cyclist is producing on his own do not change because both factors are not dependent on the speed of the motor.

2.1.2. Friction force on the front wheel with hub-motor

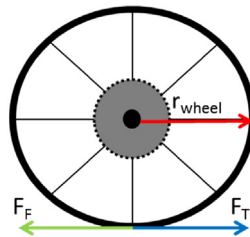
Friction calculations are required to determine if the hub-motor mounted on the front wheel creates enough force between the motor and the pavement to avoid slipping.

Fig. 7 shows the friction and driving force. If the applied force is smaller than the friction force, the wheel will not move. With a torque of 80 Nm [37] the motor can give a maximum transmission force (F_t) of 263 N. Using 0.9 as a static friction coefficient between rubber and dry asphalt [34], the equivalent weight on the front wheel (F_N) of 289 N gives a friction force (F_f) of 260 N. The transmission force (263 N) is higher than the friction force (260 N) suggesting the rotation of the wheel in the direction of propel without slipping. Thus, the motor is able to transmit a force to the ground that overcomes the friction force and propels the Trike with a rider. In the current design the majority of weight in the back and the motor mounted on the front wheel increases the chances of slipping with the lack of sufficient normal force to create enough friction. This configuration with hub motor on the front wheel was proposed to simplify the design and avoid complexity of gears. Using two hub-motors one on each rear-wheel might be an option but can give rise to synchronizing problems while driving.

2.2. Trike components

A tricycle steel frame with 24-inch diameter wheels and a 3-speed kit was selected [38]. Two independent axles on the rear-wheel provide uninterrupted driving in turns. A solar panel was

Front wheel with hub-motor



Where,

F_f - friction force (to be less than the transmission force to propel)

F_T - transmitted force (to be transmitted to the pavement in order to move the tricycle)

Fig. 7. Relationship between friction force and transmission force. Where, F_f is the friction force (to be less than the transmission force to propel) and F_T is the transmitted force (to be transmitted to the pavement in order to move the tricycle).

Table 4
Main components.

Component	Volt (v)	Current (Ah)	Power (W)	Quantity	Weight (kg)
Panel (1640 mm × 994 mm × 46 mm)	37.6	8.68	250	1	19
Battery	36	12	864	2	13.3
Motor	24–60		250–1000	1	9.7
Trike frame and 3 Wheels (Diameter 24 inches (610 mm))				1	28
Canopy (1640 mm × 994 mm × 46 mm)				1	14
Total					85

tilted at 12.5° angle to receive the maximum solar insolation during summer months [39]. A canopy was built giving the opportunity to adjust the tilt angle, the sight, and the headroom with the real tricycle design. [40]. The electric brushless DC motor (hub-motor) used for the solar-powered tricycle design has an efficiency of 83% [37].

The battery is a critical component in electric vehicles and its storage capacity largely determines the travel distance. The main reason for electric powered vehicles not being in use today is the low energy storage per unit volume in batteries [28]. Extreme temperatures negatively contribute to the performance and life of the batteries [41]. The batteries chosen for the Trike are made out of LiFePO₄ material with a high electrochemical performance and low resistance [42]. Lithium iron phosphate batteries have a higher self-discharge in comparison to other lithium-ion batteries, but they are most cost effective. The batteries are enclosed in an aluminum case and contain a battery management system with a 2 A universal charger and a life of more than 1,200 charging cycles. The combined nominal capacity of both batteries used for this research's tricycle design amounts to 864 W. Ideally, the capacity of a battery that is stated in ampere-hours (Ah) is the average current it can provide during 1 h. The capacity of a battery changes according to the applied rate of discharge [43]. The total force needed to drive the tricycle at its maximum speed of 8.90 m/s is 54.9 N. The voltage of the batteries was determined to be 39.5 V and current to be 12.4 A; the discharge time during the test drives was determined to be 87.3 min suggest the Peukert number [44] of 1.11, which suggests a relatively small internal losses in the battery.

The batteries are charged with the solar panel. The main factors influencing the power output of photovoltaic cells are the solar irradiance and the maintenance of optimal load resistance.

Various models are available to estimate of hourly solar irradiance to calculate the electricity generating capacity of the solar panels [45]. Tricycle will be mainly used during summer months in Colorado due to freezing outdoor temperature of the winter months. The weighted average solar irradiance (SR_{avg}) was computed considering seasonal variation, which equals to 548 W/m². Tilt angle of the panel is another factor for receiving insolation [46], but aerodynamic requirements to reduce wind drag and need of Trike movement limits the role of the panel tilt angle. Specifications of the Trike components are shown in Table 4.

As shown in Table 4, the total mass of the Trike is 85 kg. The solar panel (19 kg) is one of the heavier components, next to the frame. The final tricycle design and its essential components can be seen in Fig. 8.

3. Test drive results

The Trike was tested in a controlled environment (football stadium) for safety purposes – checking structural rigidity, accelerator and braking system of the Trike – before performing the actual test run on the road. The track of the football stadium has very smooth surface of rubber pavement. Relatively sharp bends on the track helped to assess the manoeuvrability of the Trike. The road is mostly a flat terrain with few slight slopes. The Trike was started with fully charged batteries having a capacity of 12 A h and 39.5 V in all test runs.

3.1. Travel range and power utilization determination

With fully charged batteries with nominal power of 864 W, the tricycle traveled for 87.3 uninterrupted minutes. While the solar panel was mounted with a capacity to produce 108 W per hour based on average solar irradiance of the test location, it is assumed that the panel charges the battery during the ride at a rate of 3 A per hour and provides an additional 10.9 min of ride. It takes around 8 h to fully charge the batteries by the solar panel alone. The Trike is designed for hybrid model (pedal or motor power) and a comparative power, torque and travel range are presented in Table 5.

As shown in Table 5, the average speeds are 5.39 m/s and 6.89 m/s for pedaling and motor powered during the test runs. Average power of 65.8 W is needed for manual pedaling. The travel range for pedaling depends on the rider's capability, whereas the motor can propel the Trike for almost 95 min. The results from the mathematical model used in this design regarding speed and travel range are close to the results from the experimental test run.

After mounting the solar panel, the Trike gets a travel time extension, which is shown in Fig. 9.



Fig. 8. Solar-powered tricycle end design.

Table 5
Pedaling vs. motor capacity.

	Pedaling	Motor powered	
		Calculated	Tested
Speed (m/s)	5.39	7.07	6.89
Torque (Nm)	3.7	16.7	varies
Power (W)	65.8	864	864
Travel range (km)	varies	42.3	
Travel time _(min)	varies	99.7	95.0

Table 6
Test-run results.

	Wind (W_{NP})	Panel connected	
		Windy(W_P)	Not windy(NW_P)
Average speed (m/s)	7.7 (0.7)	6.89 (0.2)	7.08 (0.1)
Travel time (min)	87.3 (1.5)	95.0 (1.0)	100.1 (3.0)
Travel range (km)	39.3 (0.91)	42.3 (1.09)	42.5 (1.52)

Note: Standard deviation in parentheses.

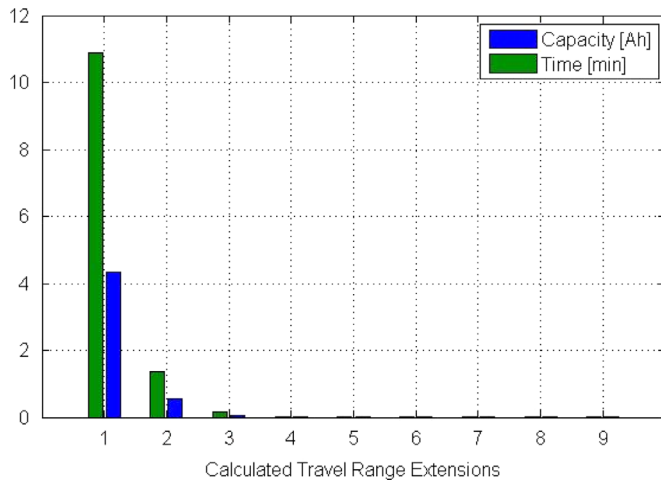


Fig. 9. Travel range extensions due to continuous solar panel charging of the batteries.

As shown in Fig. 9, during first 87 min, the solar panel recharged the battery to provide an additional 10.9 min of ride. During the 10.9 additional minutes, the panel adds another 0.544 A that provide an extension of 1.36 min. This process is continued until the recharging of the solar panel could no more offset the energy decrease of the battery to propel the Trike. The total extension time with the panel is around 12 min or a travel distance of 5 km.

3.2. Test result under different conditions

The solar-powered tricycle was tested on the road during sunny days under three different conditions: wind without panel (W_{NP}), wind with panel (W_P) and no wind with panel (NW_P). For each test condition, nine replications were made. Testing without the panel was to study the performance of the battery and to estimate the travel distance provided by a fully charged battery in a windy condition (worst case). Testing with a panel was performed to investigate the contribution of the panel to travel distance and evaluate the level of comfort provided by the shade. The windy condition was tested to investigate the amount of drag and the sturdiness of the structure supporting the panel against wind blow. Test runs were performed during windy days in the months of May and October 2013 with an average wind speed of 10–15 mph (16–24 km/h) blowing [47]. Test results with wind consideration are shown in Table 6.

As shown in Table 6, the time difference between the solar panel being connected to the batteries (W_P) and the solar panel being not connected under windy conditions (W_{NP}) is 7.70 min. In statistical paired t-tests with a 95% confidence interval, the travel range for windy conditions with a panel connected (W_P) is greater than windy conditions without a panel (W_{NP}). The panel connected to the batteries increases the travel distance. The panels and the Trike were stable during the wind although some whistling sound was heard. The travel range under windy conditions with the panel (W_P) is smaller than travel range without wind and the panel connected to the batteries (NW_P). In summary, either windy or not, the panel supported a higher travel range.

As an electrical performance, charging and discharging rates are crucial to determine the charging time and resulting travel time. The rate of battery discharge is shown in Fig. 10.

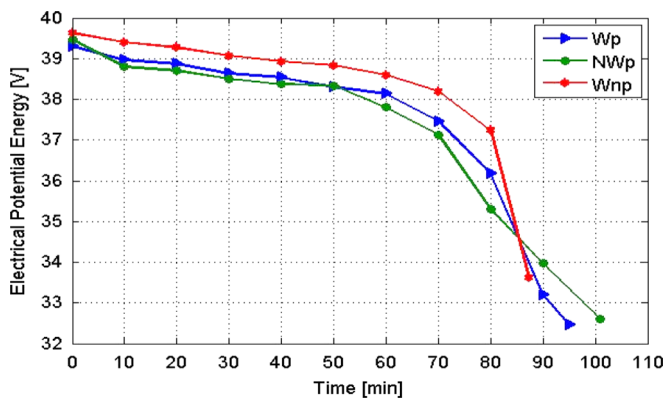


Fig. 10. Electrical potential energy of the batteries under different conditions.

As shown in Fig. 10, in all test conditions and Trike configurations, the discharge rate appears similar for a while (up to 40 min). Towards the end, the voltage drops faster with no panels. When the solar panel is not connected to the batteries, the Trike stops running after the voltage dropped below 33.6 V, whereas with the solar panel connected, the Trike runs until the voltage dropped to 32.5 V. This difference contributes to average speeds and travel ranges. The lower average speed noticed towards the end of the test drive is directly related to the voltage drop in the batteries.

On another note, depending on the weather conditions, the power usage fluctuates. For example, head wind reduces the tricycle's total runtime. When the wind blows harder, the power needed to propel the tricycle at a constant speed needs to be higher. From the design and test runs, it is clear that the solar Trike is technically feasible for low speed and relatively short commutes. Environmental and economical performance is presented next.

4. Environmental and economical analysis

The Life Cycle Analysis (LCA) approach is used to evaluate the environmental and economical impacts of the solar Trike. A three dimensional model of the Trike was created in SolidWorks in CAD Laboratory and the major machining, and assembly work is done in a machine shop, both at Colorado State University-Pueblo. For the sustainability analysis, the region of manufacturing was selected as Southeast Asia and the region of use is set to be North America, which is the intended location of use. Transportation by ship was used for all parts because this is the most economical way to transport goods over long distances. After assessing the tricycle's parts, the values for water eutrophication, air acidification, total energy consumed, and carbon footprint were established.

4.1. Emission determination

The commonly used lifecycle impact categories that can result from manufacturing products are global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical smog, aquatic toxicity, human health, resource depletion, water use and land use. A product's life is divided into manufacturing stage, transportation, use and disposal for impact assessment. Travel distance, mode of transportation and quality of the fuel are the main factors in Transportation [48]. Energy consumption, water eutrophication, air acidification and carbon footprints are used as key environmental indicators. Emissions of the mechanical components were determined by the sustainability module in SolidWorks, whereas a weight-based relationship is used for electrical components and both are presented in Table 7.

Table 7
Combined environmental impact of the tricycle.

	Water Eutrophication [kg PO ₄]	Air Acidification [kg SO ₂]	Total Energy Consumed [MJ]	Carbon Footprint [kg CO ₂]
Mechanical total	0.168	1.18	2,503	201
Solar panel frame	0.016	0.236	540	46.8
Solar panel	–	–	4,401	–
Batteries	0.0083	0.227	1,870	144
Hub-motor	0.192	0.888	960	92
Grand total	0.384 kg PO₄	2.53 kg SO₂	10,274 MJ	484 kg CO₂

Table 7 shows the combined environmental impact of all mechanical tricycle parts, the frame that will hold the solar panel in place, the batteries, the hub-motor, and the solar panel. The emissions-value for the solar panel is lumped into the yearly kWh utilization [49].

The motor, including the rim, weighs 10 kg. Based on the battery life-cycle analyses, an established average value for kg CO₂ emissions is 12.5 kg/kg battery cell [50]. Energy consumption of 165 MJ/kg is used to include all possible energy consumptions while producing the material and manufacturing the battery [50]. The battery cell weight of 8.87 kg needs a total energy consumption of 1,463 MJ, and the total CO₂ emission of 111 kg is determined considering the manufacturing process.

In order to be able to determine Btu/pass-mi and the CO₂ emissions in g/pass-mi, the lifespan of the tricycle was determined, which is 10 years based on the lifespan of its critical components (solar panel) [51]. Driving the tricycle 90 days/year for 37.1 km/day leads to a total of 3330 annual passenger kilometers.

For Trike manufacturing, the total energy consumption is 505 Btu/pass-mi (2,850 kWh), and annual CO₂ emission is 51,830 g (23.5 in g/pass-mi). The Btu/pass-mi of the Trike is 58.9% of the lowest examined mode of existing transportation (Heavy Rail). The CO₂ emission per g/pass-mi is as low as 24.3% of the lowest comparable mode of transportation (van pool). In other words, introducing the solar Trike proposed in this research as an independent mode of transportation can help to reduce the Btu/pass-mi by more than 41% and mitigate the effect of CO₂ emissions per g/pass-mi by more than 75%.

4.2. Economic analysis

The Trike parts and components are acquired from different sources. The costs were derived from a combination of the retail and wholesale prices of the products as per their availability. A five percent maintenance cost is assumed and used for the economical analysis [52]. The total cost of the Trike is estimated to be \$2,500. For cost of emission, a price of \$8.3 per ton CO₂ is used [53]. If the Trike is powered fully by the solar panel, the emissions during use will be zero. In this case, the manufacturing and disposal phases only contribute to CO₂ emission, which is 518 kg presented in the previous section. Using a price of \$8.3 per 1,000 kg of CO₂ emissions, the production and disposal process emission for CO₂ created costs of \$4.3. Distributing this amount over the lifespan of the Trike gives an annual cost of \$0.43. With the cost of \$0.000731 per watt, for a battery with 432 W storage capacity, the price per charging cycle leads to \$0.315. The battery will be charged 90 times per year as per the travel assumption made earlier. A utility cost function (UCF) is presented as follows:

$$UCF_{\text{annual}} = CO_2^{\text{annual}} + DI^{\text{annual}} + M^{\text{annual}} + \sum_{i=1}^2 \alpha N_i S \quad (4)$$

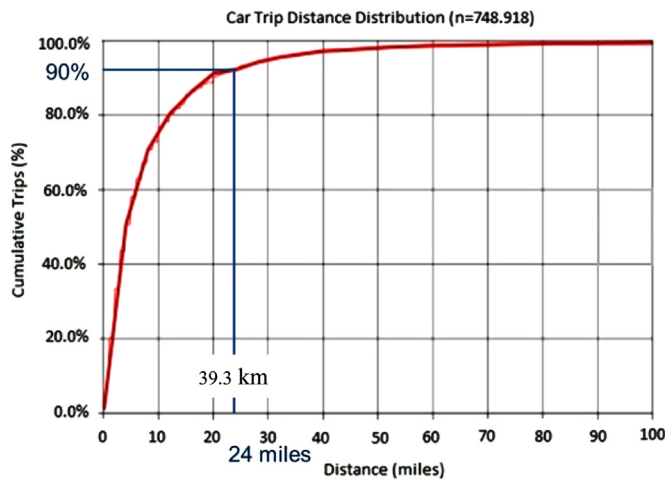


Fig. 11. Solar Trike in a graph of cumulative distribution of driven miles per trip.

where, CO_2^{annual} is the annual CO_2 emission cost due to the production process of the tricycle, DI^{annual} is the design and installation costs of the solar-powered tricycle, M^{annual} is the annual maintenance costs as a fixed percentage share of the cost price, S is the cost to fully charge the battery, α is the number of charging per year and N_i is the total number of storage units

Including all the aforementioned cost factors into the utility cost function (UCF), the annual cost of operating the Trike could be \$417.

4.3. Discussion

The maximum speed of the tricycle is 32.1 km/h. When the solar panel is not connected, the average speed was 25.5 km/h and travel range is 37.1 km. The average speed is lowest under windy conditions at 24.8 km/h and a travel range of 39.3 km; the longer travel distance was observed even with lower velocity with a panel. Lower velocity might be due to the additional weight of the panel and additional drag resulting from the panel surface. The extra travel distance was achieved from the recharging by the panel during the travel time. This suggests an applicability of the solar Trike, and its relevance to the cumulative trip distance in the United States is shown in Fig. 11.

As shown in Fig. 11, a travel range of 39.3 km (24.5 mile) reveals that more than 90% of driven miles per trip in the United States can be covered by the proposed solar-powered Trike. Furthermore, the occupancy rate is also higher (100%) as the Trike is designed as a one-person vehicle and will always have full occupancy.

In inclined planes with angles greater than 10° , the driving wheel starts slipping because the majority of weight is on the rear of the Trike. The height of the solar panel canopy appeared to be too high, which might cause to shift the center of gravity and was initially feared that this could challenge the stability of the Trike in the turns or during wind conditions. However, it was tested safe while driving in a 180° turn with full speed. A completely depleted battery needs around 8 h to be fully recharged by the solar panel and less than 6 h if charged from an electric outlet.

According to the U.S. Energy Information Administration [54], the price for 1 kWh in the transportation sector is \$0.1044 (as of September 2013). The two batteries used for the solar-powered tricycle account for a total of 864 W. One full charge for the two batteries costs \$ 0.0902 when charging from an electric outlet. The annual ownership cost of the Trike is \$417. In reference to U.S. gasoline price of \$3.425 per gallon (\$0.90/liter), (as of 30 September, 2013) for the least driving 4,785 mile/year (7700 km/year) age

group of over age 65 [55], driving 3,660 miles (5889 km) on Trike can save significant cost of car ownership.

The solar Trike might be more relevant to commuters living in small towns without public transportation (train or bus services and need to rely on the car with no choice). The solar Trike, with its compact design, offers a good physical exercise option from pedaling thus helping the riders for healthy living. No pollution and the smaller size of the Trike foster cleaner cities and spare spacious sidewalks where people get a chance to interact personally and socialize [56], ultimately helping to build a community by freeing people from the high speed confinement of cars and bringing them together.

5. Conclusion

A sustainable mean of transportation is proposed in this paper. The Trike was designed and tested. Torque and power requirements for a single rider were computed for both motor driven and manual pedaling; its applicability for the local commute is examined. Environmental impact analysis performed as a part of sustainable design suggests that solar-powered tricycle is more environmental friendly than other modes of transportation. The solar-powered tricycle design proposed in this research has considerably low energy usage and CO_2 generation; this makes the tricycle a least polluting and least energy consuming mode of transportation among the available transportation options. It is also evident that the Trike has a travel range that can meet the 90% travel need in United States. The higher occupancy rate and lower cost of ownership suggested solar Trike as an affordable means of transportation.

The solar-powered tricycle was tested in Colorado, USA. Due to the dry and sunny climate, the Trike can be useful as an alternative mode of transportation. Although it is not suitable for high speed freeways, the tricycle might be a second vehicle that can satisfy the travel needs for urban commuters avoiding congestion, parking hassles or fears of contributing to Greenhouse Gas emissions. The solar panel helps to go extra miles in addition to providing good shading during high sunny days in a semi-arid climate and proved to be a feasible sustainable alternative for a local commute.

6. Limitations and recommendations for further research

The practicability of the solar-powered tricycle might be limited based on climatic conditions; places with low solar irradiance and rainy seasons might not be able to receive the same benefit. Required speed and weight of the person riding the Trike and type of terrain play a role for the design to work in addition to solar insolation. It will take longer time to charge the battery in lower insolation and the battery will discharge faster to carry a heavier rider. For a panel with 2 A/h charging rate, it will take more than 12 h to fully charge the battery and limits the design. Minimum weighted average insolation for best operation of this design is 540 W/m^2 . When driving in windy conditions, the rider may feel difficulty in manoeuvring the Trike, which could be improved by lowering the tricycle frame and panel height. Bringing it closer to a recumbent position will lower the center of gravity, and mounting a windshield in the front could reduce the encountered aerodynamic drag and extend the driver's comfort and travel distance.

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